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The Interactive Multisensor Analysis Training System:
Using Scientific Visualization Technology to Teach Complex Cognitive Skills

Sandra K. Wetzel-Smith
Carl Czech

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Sandra K. Wetzel-Smith
Navy Personnel Research and Development Center

Carl Czech
Planning Systems Incorporated

Reviewed by
Wallace H. Wulfeck II

Approved by
J. McLachlan
Director
Classroom and Afloat Training

Released by
P.M. Spishock
Captain, U. S. Navy
Commanding Officer
and
Murray W. Rowe
Technical Director

Navy Personnel Research and Development Center
53335 Ryne Road
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Successful operation of airborne weapons and sensor systems demands that operators and tacticians possess high-level understanding of how environments and potential targets interact so they may best configure onboard suites. The complex cognitive skills required can only be the product of appropriately designed training, especially when opportunities for practice are limited. The Interactive Multisensor Analysis Training (IMAT) System uses advanced scientific visualization technology to conceptually present the interactions among sensors, and environments in realistic mission scenarios. Using approved Navy, Department of Defense, and other suitable databases (e.g. DBDB-5, ANDES), IMAT computers and display systems transform the data into understandable graphic formats. As support for cognitive skill oriented training programs, IMAT has provoked a new approach to instructional design. The IMAT approach promises to increase training efficiency and effectiveness in complex warfare areas such as anti-submarine, electronic, and mine countermeasures by accelerating the development of domain expertise and improving trainee performance during training. IMAT may also be appropriately applied to other complex cognitive skill domains inside and outside the Department of Defense, including technical training and education in meteorology, oceanography, geology, ecology, and disaster preparedness.

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Foreword

This report was prepared under the 6.3 Manpower, Personnel, and Training Advanced Technical Development Program Element 0603707N (Work Unit 063707N.L2335.IM001). The goal of this study was to present a conceptual overview of the Interactive Multisensor Analysis Training (IMAT) System and briefly summarize the results of a preliminary evaluation.

Any questions regarding this report should be directed to Sandra K. Wetzel-Smith, Code 13, (619) 553-7693 or DSN 553-7693.

P. M. SPISHOCK
Captain, U.S. Navy
Commanding Officer

MURRAY W. ROWE
Technical Director

Summary

Problem and Background

Antisubmarine Warfare (ASW), like most modern warfare, demands the successful performance of complex cognitive tasks, which in turn requires specialized training. The challenges facing Antisubmarine Warfare (ASW) training in the closing years of this decade are greater than at any time since the early days of World War II. Conditions since the end of the Cold War, and those expected throughout the next decade, impose additional complexity on maintaining our ASW superiority. Russian nuclear submarine technology continues to improve and advanced submarines continue to be built and delivered to their fleet. Concurrently, the proliferation of improved diesel submarine technology to many Third World nations requires that our ASW forces also be capable of conducting operations in the vastly different littoral regions. Effective instruction for the complex cognitive tasks and skills required for the successful conduct of ASW hinges on presenting the interrelationships among targets, sensors, and their shared three-dimensional world.

The training challenge is two-fold: (1) retaining the capability to detect and prosecute nuclear submarines; and (2) expanding our current capability against diesel submarines of the Third World. When coupled with dramatic reductions in ASW training resources, including at-sea training, this historic change compels the development of training for skills learned previously on the job and for skills required in new environments.

Until recently, technical training for complex tasks depended almost entirely on relatively crude graphic depictions and verbal descriptions. This report describes one promising approach that combines computer technology and innovative instructional design the Interactive Multisensor Analysis Training System (IMAT). The IMAT approach to training defines complex cognitive skills, employs a specialized instructional design approach derived from state-of-the-art instructional design theory, uses contextualized warfare task oriented instruction, and engages learners by use of scientific visualization strategies. This report provides a working definition of complex cognitive skills, briefly describes the field of scientific visualization, illustrates the use of IMAT, and summarizes the results of a preliminary evaluation of training programs using the IMAT system.

Complex Cognitive Skills Demand a Specialized Instructional Approach

IMAT is used to best effect in training complex cognitive skills. Subject-matter domains may be considered complex by distinct attributes of procedures, processes, and principles. They are:

- **Abstractness**. Physical phenomena or causation may not be readily visible.
- **Continuity**. Physical phenomena and their effects are routinely described as points on a continuum, rather than in discrete steps.
- **Non-linearity**. The continua contain varying rates of change, intensity, etc.
- **Dynamic state**. Interactions occur on a continual basis and present continuously evolving circumstances.

- **Simultaneity**. Changes in a target-environment-sensor dynamic are linked and interwoven.

- **Interactivity**. Processes within a domain may be strongly interactive, even as individual phenomena may be complex in their own right.

- **Conditionality**. Practical uses of principles learned in training are likely to be highly contextualized in a real-world warfare environment.

Instruction in these difficult domains have usually consisted of rote memory of facts, drilled procedures, and part-task simulations. Training materials in most learning environments have been limited to two-dimensional representations of changing relationships in 3-D space. Given the technology available, learner achievement has often been measured by the ability to recite verbal descriptions, rather than demonstrations of understanding manifested in mission-related predictions and decisions.

New computer technology allows the use of scientific visualization in a classroom environment. Scientific Visualization is the discipline of rendering complicated (and often invisible) phenomena in graphically clear ways. IMAT is an instructional "enabler" that allows instructors to guide students to accurate conclusions to complicated problems. By manipulating data, changing the values in interacting variables, learners can see the effect of changes in environment, targets, or sensor systems. The IMAT workstation contains approved data bases, prediction models, and simulation software that permit "on-the-fly" responses to the needs of the class.

Evaluation Results

IMAT-based instruction has been instituted in two Navy basic acoustical oceanography courses. Compared to a traditional course in the same domain, the IMAT course has improved training effectiveness resulting in significantly higher scores on a specialized test measuring recall of facts, comprehension, and cognitive skills. In addition, preliminary data suggest that IMAT accelerates the development of expertise because the knowledge structures of IMAT-trained novices are closer to that of experts than to that of the average journeyman operator.

Potential Applications

IMAT, with its innovative use of scientific visualization and contextually-anchored instruction, holds promise for warfare domains that require complex cognitive skills. Additionally, the use of instructional designs using IMAT technology has the potential for application in non-defense related fields including meteorology, environmental predictions, disaster preparedness, and any other subject matter that depends on understanding physical science principles.

Contents

Introduction

Problem and Background

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The training challenge is two-fold: (1) retaining the capability to detect and prosecute nuclear submarines; and (2) expanding our current capability against diesel submarines of the Third World. When coupled with dramatic reductions in ASW training resources, including at-sea training, this historic change compels the development of training for skills learned previously on the job and for skills required in new environments.

Successful performance of complex cognitive tasks requires very specialized training. The critical skills in the highly variable ASW domain require sensor operators and tacticians to integrate threat, environment, and system component information. The best practitioners have always been able to derive the best solutions through sophisticated reasoning—what observers might call a "sixth sense." Closer scrutiny of top performance reveals profound conceptual understanding of complex interrelationships among sensor systems, environmental effects, and the targets of interest.

Capturing the essence of those seemingly intuitive skills and conceptualizations is one of the most daunting challenges facing military trainers today. Until recently, technical training for complex tasks depended almost entirely on relatively crude graphic depictions and verbal descriptions. This report describes one promising approach that combines computer technology and innovative instructional design --the Interactive Multisensor Analysis Training System (IMAT). The IMAT approach to training defines complex cognitive skills, employs a specialized instructional design approach derived from state-of-the-art instructional design theory, uses contextualized warfare task oriented instruction, and engages learners by use of scientific visualization strategies. In brief, this report provides a working definition of complex cognitive skills, briefly describes the field of scientific visualization, illustrates the use of IMAT, and summarizes the results of a preliminary evaluation of training programs using the IMAT system.

The Characteristics of Complex Cognitive Skills

Appropriate application of training technology and instructional design depends first on establishing the level of complexity in the targeted performance. In practice, designers and analysts usually combine study of the subject matter, measures of optimum performance, and accomplishment of the job itself. Documentation, observation, and interviews play roles of varying importance, depending on the nature of the target skills. In some cases, the analysis is relatively straightforward and the complexity readily evident. As jobs depend more on analysis, judgment, and decision-making, proper task analysis becomes more complicated. Simple observation of expert practitioners may not only fail to reveal how they complete their task, but also leave hidden the level of complexity in the task itself.

Subject-matter domains may be considered complex by virtue of distinct attributes of procedures, processes, and principles. A well-designed task analysis is likely to uncover a number of dimensions that make them uniquely challenging. Research in other content areas has helped distill a wide range of considerations into a helpful list of attributes common to tasks requiring complex cognitive skills (Feltovich, Spiro, & Coulson, 1991). They include:

- **Abstractness (versus concreteness)**. Physical phenomena or causation may not be readily visible. Examples would be phenomena such as propagation of sound through sea-water or electron flow through a conductor. The attendant cause-and-effect relationships are only evident as the product of many invisible interactions. Likewise, terms like "propagation loss" or "absorption" may best be expressed mathematically. Although learners can become relatively facile at manipulating mathematical constructs, the truly significant *effects* could remain transparent to them.

- **Continuity (versus discreteness)**. Many physical phenomena and their effects are routinely described as points on a continuum, but real understanding defies such oversimplification. By focusing on discrete points of a continuous phenomenon in progression, learners have to develop a feel for trend and flow on their own, rather than by observing it directly.

- **Non-linearity** (versus linearity). Similar to continuity in terms of description and understanding, are non-linear effects. For example, spreading loss is a concept in acoustical oceanography that is manifested non-linearly—doubling the transmission distance does *not* halve the level of the sound at the receiver. The prediction of spreading loss also depends on a given propagation path, compounding the cognitive challenge.

- **Dynamic state** (versus static). Even though pertinent examples may be inadequately represented by a frozen moment in time, traditional instructional technologies may force learners to comprehend dynamic events captured in a series of snapshots. Oceanographic and atmospheric variability, for example, affects sensor and weapons operation on a continual basis. A basis of understanding that is built on instances rather than animate progression may constrain later performance in rapidly evolving mission scenarios.

- **Simultaneity** (versus sequentiality). Changes in the target-environment-system dynamic are inexorably linked and interwoven. Important events are overlapped or concurrent. Each major influence in the task situation must be understood on a fundamental level, or operators and tacticians will have difficulty integrating them on the job.

- **Interactivity** (versus separability). Processes within the domain may be strongly interactive, even as individual phenomena may be complex in their own right. The task becomes many times more complicated when cause- and-effect relationships exist between and among them. Examples are easily found in signal propagation models that apply to both the acoustic and electromagnetic spectra. There are dozens of variables and hundreds of combinations that may profoundly affect transmission paths, strengths, and usability of sound or radio waves in a given environment.

- **Conditionality** (versus universality). Although principles may be applied universally in scientific or technical terms, practical uses in a warfare environment are likely to be highly contextualized. This becomes a particularly difficult problem when complex subject matter is reduced to a collection of heuristics for ease of teaching. For instance, rules that apply to the use of sonar in deep oceans may be transferred inappropriately to use in shallow, littoral areas. The physical laws have not changed, but incomplete, over-simplified understanding of them may make proper operational decisions counterintuitive to on-station operators.

Antisubmarine Warfare must respond to a wide range of challenges that encompasses many or all of these attributes. In ASW, tacticians and sensor operators pit their skills against an unseen enemy in a changeable ocean. The target's vulnerability is determined by its particular mission, operations, propulsion, design, and placement within its environment. Finally, the detecting system has to be configured appropriately in anticipation of ranges and sensitivities predicted by historical databases, on-station temperature measurements, and a "best guess" of the submarine commander's intentions.

Warfare in the electromagnetic spectrum is no easier. The environmental variables affecting radio waves are equally invisible, subject to the vagaries of atmospheric composition and variability, and even more unpredictable from minute to minute than those in the acoustic spectrum. Operators in this theater are generally engaged in fast-paced scenarios where even relatively unsophisticated sensor equipment can aid the enemy in counterdetecting our intentions. In passive detection, monitoring, and active prosecution, operational success depends on proper placement of sensors in an environment continually affected by large and small weather systems, seasonal changes, and diurnal effects.

The Importance of a Cognitive Instructional Approach

Traditionally, instruction in these difficult domains depended on rote memory of facts, drilled procedures, and part-task simulations. Where changeable physical phenomena were involved, training materials were limited to two-dimensional representations of 3-D space. When necessary, the fourth dimension of time may have been superimposed on an artificially "flat" world. Achievement, under these circumstances, was usually measured by students' ability to recite verbal descriptions of complex physical interactions, rather than use their understanding to develop mission-related predictions and decisions. For instance, most successful students could answer questions about ocean temperature layers and their boundaries, but were never asked to accurately predict their effect on the character of a submarine's detectable acoustic signature.

In many ways, these methods were adequate to large segments of basic, apprentice-level tasks. Apprentices were expected to gain deeper understanding on the job, under the guidance of accomplished journeymen. The operational circumstances readily supported the approach, especially when school graduates became part of mission-oriented teams. Even when apprentices were expected to perform as solitary operators, enough experience existed among colleagues in the field that productive mentor-protégé relationships could develop. Finally, a forward-deployed and technologically aggressive potential adversary, the Soviet Union, fielded large numbers of units that provided real-world practice. In this decade, circumstances have changed enough to warrant serious concern. Operator skills are no less critical today, but practice opportunities have become fewer, while the corporate expertise of on-station practitioners is diminishing rapidly. Our aim must be to capture the essence of expertise, while fielding new ways to promote transferable and maintainable skills.

New computer technology has given rise to an expanded field of "scientific visualization." The core discipline of rendering complicated (and often unseen) phenomena in graphically clear ways is not new, but powerful microprocessors and mass digital data storage have enabled scientists to depict them with great clarity. Once the domain of large mainframe computers, effective visualizations are now possible on relatively modest workstations. It is not inconceivable that today's most advanced work will be performed on personal computers in the foreseeable future.

The Principles of Scientific Visualization

Scientific visualization has traditionally been used in two roles: exploration and presentation (Bryson, 1994). Past technological constraints have limited its use almost entirely to research applications. As a study tool, it required considerable up-front knowledge of the subject at hand. When used for presentation, scientists routinely selected a data set, transformed it, then turned it over to specialized graphic artists who rendered the appropriate images, often adding animation. End products designed for laymen or learners were relatively rare. Most visualizations were intended for other scientists. IMAT aims to bring the technology into specialized technical training by adhering to some basic principles.

Mere representation of data is *not* the aim of scientific visualization. The goal is to communicate meaning. At its best, visualization will "create complete images that 'speak' to the viewer without additional explanation" (Keller & Keller, 1993). Physical phenomena, not the data they stem from, are the focus of the visualization. Learners must be able to derive meaning without having to interpret the display or apply an algorithm.

The following are attributes for excellence in graphical displays of data (Tufte, 1983). They are particularly germane to scientific visualization and critical to computer manipulation of large data sets for instructional purposes. Graphical displays should:

- **avoid distorting what the data have to say**. Presentations must not overstate or oversimplify to the point of inducing misinterpretation.

- **encourage the eye to compare different pieces of data**. When depicting the interaction between two physical phenomena, for instance, the relationship should be clear and easily discernible.

- **reveal the data at several levels of detail, from a broad overview to the fine structure**. Viewers should be able to get the "feel" of displayed data quickly, then have the opportunity to explore specific points.

- **serve a clear purpose**. No engaged viewer should have to guess at the presentations intent.

- **be closely integrated with the verbal descriptions of a data set**. Any scientific visualization will complement other materials that describe the content of interest. In technical training, lessonware must be carefully aligned with displays.

These are not simple things to accomplish. Development of scientific visualizations is an iterative process often involving many cycles of trial and refinement.

The Interactive Multisensor Analysis Training System

Solutions to problems of system operation, tactical employment, team integration, and crew coordination all require the development of training methods to improve students' ability to understand the multi-dimensional properties and interrelationships of sensor-system operation.

Key to scientific visualization in training is the transformation of data representations, such as ocean environmental databases, into easily understood presentations of actual phenomena. An example would be transmission loss in sound emanating from a submarine. The interacting variables in this case are linked to frequency of the sound, the path it takes though the medium, reflections, absorption, and any number of intersections with unseen acoustical ducts, layers, and boundaries. The calculations of effect, daunting to a physical scientist, are likely to be incomprehensible to a novice sensor operator.

The Interactive Multisensor Analysis Training (IMAT) employs a multi-use concept display training aid that provides three-dimensional representations of cause-and-effect relationships. Using IMAT, instructors may now display a wide range of scenarios that reflect the input of real environmental databases, sensor characteristics, and target parameters. An easy to use computer interface allows on-the-fly classroom simulation of "what-if" scenarios, mission replays, and decision analyses. ASW operators can now see refraction of sound waves, EW tacticians may see the realistic results of emitter placement in a heterogeneous atmosphere, and mine warfare analysts can match countermeasure to threat by manipulating variables.

Based on a powerful graphics workstation, IMAT is an instructional enabler that is spurring new approaches to complex cognitive skills training. By anchoring instruction in mission-related context, course designers have created learning environments where students are guided to accurate conclusions to complicated problems. Judgment and decision-making skills, based on understanding, have replaced much of the "drill and kill" associated with memorization of facts.

In domains containing large numbers of interactive variables, the success of individual operators and tacticians depends on transferring true conceptual understanding to any number of unique scenarios. This requirement to problem-solve when faced with novel situations demands a careful and disciplined approach to skill training that simplifies without trivializing. It must also present a large number of high-fidelity examples in a short period of time.

Introductory learning is often taught as a series of topics, each content area presented in isolation from others. This compartmentalizing has been (and remains) a part of many airborne weapons systems training programs. Unfortunately, when learners are forced to merge these chunks of knowledge, the result is too often an inferential leap of faith into profound misunderstanding. Driven by a very real need to order and integrate their new knowledge, students will invariably force pieces of the content puzzle together in ways that severely distort the picture.

Such early mistakes and missteps are not easily corrected by remediation. If flaws go undetected or uncorrected, they certainly will not be obviated by follow-on or fleet training. Indeed, there is ample evidence to suggest that poorly designed, delivered, or received introductory instruction may interfere with advanced learning (Feltovich, et al., 1989).

Regardless of experience level, all practitioners in complex domains may benefit from scientific visualization as part of contextualized instruction. The ability to make predictions and gain immediate, verifiable feedback from realistic data-driven scenarios should reinforce prior learning while bringing on station experience into sharper focus. The use of actual mission data, regenerated and presented on IMAT, could allow fleet operators to explore situations similar to those they are personally familiar with. IMAT goes beyond simple simulation however, and is distinctly different in application than common display devices.

If instructional designers' intent was to merely show physical phenomena, such as refraction of waves in a heterogeneous environment, they might easily use animations that any personal computer is capable of displaying. The scenarios could even be stored in another medium, such as videotape or disc. Such approaches, though useful, only allow for canned experiences. They are not necessarily an inroad to profound conceptualization. IMAT facilitates "reflective cognition."

Donald Norman (1993) describes reflective reasoning as an important part of restructuring facts and practice into the type of expertise required of complex cognitive tasks. When describing it he says:

> Reflective reasoning does not have the same kind of limits on the depth of reasoning that apply to experiential cognition, but the price one pays is slow and laborious. Reflective thought requires the ability to store temporary results, to make inferences from stored knowledge, and to follow chains of reasoning backward and forward, sometimes backtracking when a promising line of thought proves to be unfruitful. (p. 25)

IMAT provides a classroom aid that becomes part of an invigorating learning environment. As an advanced tool, it mitigates much of the "slow and laborious" aspects of reflective cognition by storing knowledge (approved databases), and then allowing chained reasoning (by manipulating values and variables). It also provides a means to experiment and engage in carefully guided "what if" exercises that engage groups of learners synergistically. IMAT gives instructors the ability to define their media representations in light of the training task at hand. They need not be relegated to rigidly composed and sequenced examples—snapshots that try to explain without giving the option to explore.

In best use, IMAT will blend into the learning environment to the point it becomes "invisible." As development progresses, the computer interface, curriculum design, and instructor technique will all contribute to the ideally seamless integration of scientific visualization technology. Nor will IMAT stand alone. Ancillary materials, such as instructor guides, trainee technical manuals, and complementary presentation media must take into account the unique facilities of IMAT.

Although IMAT, scientific visualization, and contextually-anchored instruction promise improved initial performance in the fleet, their most important contribution is likely to be in increased *potential.* The strong conceptual foundations they may provide will enhance knowledge gained after formal training and fine-tune skills during practical application.

Results

Early evaluations of IMAT-based curricula have been extremely promising. Acoustical oceanography students in redesigned courses learn significantly more material in the same amount of time, and are able to better derive accurate solutions to novel multivariate problems than non-IMAT trained learners. Table 1 summarizes results of an evaluation conducted at the Sonar Technician (G) Class A School at the Fleet ASW Training Center, San Diego and the Aviation Warfare Systems Operator Class A School at the Naval Air Technical Training Center, Millington, Tennessee (see Wetzel-Smith, Ellis, Reynolds, & Wulfeck, 1995 for additional details).

Table 1

Performance on the Acoustical Oceanography Unit Test by AW IMAT versus STG IMAT versus STG traditionally-trained students (All effects are significant to the .01 level)

	Question Types			
	Facts (N = 32 (%)	Comprehension (N = 15) (%)	Cognitive Skills (N = 16) (%)	Total (N = 63) (%)
STG Traditional (N = 90)	79.5	63.2	62.4	71.3
STG IMAT (N = 71)	89.0	76.0	77.2	82.9
AW IMAT (N = 46)	94.9	87.8	83.8	90.4

Preliminary data also suggest that IMAT accelerates the development expertise because the structural knowledge of IMAT-trained novices is closer to that of experts than to that of the average journeyman operator. Although much work remains to be done, stakeholders in many warfare specialties have focused on IMAT and context-based training for their potential promise in an era of broadened demands.

Future Applications

Weapon systems are becoming more integrated. This technology-driven trend in design, manufacture, and employment presents special problems to operators, and therefore to interface specialists, instructional designers, and trainers. As capability and functionality in equipment become linked, system effectiveness is a product of a larger number of variables, both internal and external to the system. These smart machines require smarter people. While many subtasks can be deskilled, expert operation that depends on inherent understanding of real-world nuance cannot. Despite technology—and because of it—there are no indications that our jobs will become less complicated. Indeed, tactical and strategic doctrine call for increased integration and cooperation in complex environments, often with very short notice. Warfare specialists may continue to dominate design and development, but the future is likely to demand a high degree of generalization as fewer people operate very capable multi-function systems. Every corner of military training will be affected. Some of the warfare specialties that will benefit from IMAT technology are listed below:

Antisubmarine Warfare

IMAT is already an important part of apprentice training for Aviation Warfare Systems Operators. Much of the content that is common to other sonar specialties in the surface and submarine communities is being transferred to those Class A schools. Tactician training is also gaining the IMAT advantage. Tactical Coordinators in the Maritime Patrol community are receiving instruction from specialized operational training detachments. Sea-based tacticians have IMAT available as part of their fleet training. As the project expands, more opportunities for fleet training, pre-deployment briefs, refresher sessions, and recurrent evaluations are becoming obvious. The context-oriented nature of IMAT applications make them a natural for journeyman and expert programs.

Electronic Warfare

The electromagnetic spectrum, including environment, emitters, receivers, and countermeasures, is easily one of the most complex skill domains in air warfare. Although signal analysis and recognition may be heavily job-aided through the use of on-line classification aids and alert systems, appropriate reactions to real-world stimuli often depend on the understanding of atmospherics, radiowave propagation, and system characteristics. Performance in rapidly evolving tactical scenarios depends quite heavily on being able to anticipate the effects of likely combinations of variables. IMAT-trained fleet practitioners will have skills that allow them to make the best use of environmental predictions, system configurations, and operational intelligence.

Mine Countermeasures

No other warfare area is faced with as wide a range of threats as mine countermeasures. It is also one in which the consequences of inappropriate performance are particularly quick and unforgiving. Millions of potentially lethal weapons are wielded by likely first- and third-world adversaries. At one end of a broad continuum, the implements of mine warfare include "smart" weapons capable of selectively attacking appropriate targets. On the other end, less sophisticated technology dates back to the first World War. Regardless of design, even the threat of a crude mine can change the battle picture. The tactical environments are no less complicated than in other warfare areas, particularly since detonation may be initiated by sound, pressure, or electromagnetic influence. Detection equipment and techniques span a correspondingly wide spectrum that includes systems designed for land and sea. IMAT may be used to train specialists and tacticians who operate ashore and afloat.

Other Domains

Any subject matter area that encompasses a large number of variables, uses extensive numerical databases, and requires complex cognitive skills may benefit from IMAT. Meteorology, for instance, combines a large number of variables documented in huge databases. By using historical data or by manipulating critical values in "what-if" situations, students could develop strong conceptual understanding of large weather patterns, local variability, and the critical aspects of observations and forecasts. Some of the same concepts are used by disaster preparedness specialists to predict nuclear, chemical, or biological disbursement patterns. By combining known properties of hazardous agents with environmental predictions, learners could see the reasoning behind effective evacuation and countermeasure planning. Virtually any subject-matter that depends on understanding physical science principles may find IMAT and scientific visualization technology a useful instructional tool.

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Director, Army TRADOC Systems Analysis Activity
Armstrong Laboratory, Operations and Support Directorate (AL/DO), Brooks Air Force Base, TX
Air Force Air Training Command
Superintendent, Naval Postgraduate School
Institute for Defense Analyses, Science and Technology Division
Pentagon Library
Defense Technical Information Center (DTIC) (4)